P6.6 A CHARACTERIZATION OF THE TERRESTRIAL ENVIRONMENT OF KODIAK, ALASKA FOR THE DESIGN DEVELOPMENT, AND OPERATION OF LAUNCH VEHICLES

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1. Importance of Natural Terrestrial Environment Definitions

A quantitative characterization of the terrestrial environment is an important component in the success of a launch vehicle program. Environmental factors such as winds, atmospheric thermodynamics, precipitation, fog, and cloud characteristics are among many parameters that must be accurately defined for flight success. The National Aeronautics and Space Administration (NASA) is currently coordinating weather support and performing analysis for the launch of a NASA payload from a new facility located at Kodiak Island, Alaska in late 2001 (NASA, 1999). Following the first launch from the Kodiak Launch Complex, an Air Force intercontinental ballistic missile on November 5, 1999, the site's developer, the Alaska Aerospace Development Corporation (AADC), is hoping to acquire a sizable share of the many launches that will occur over the next decade. One such customer is NASA, which is planning to launch the Vegetation Canopy Lidar satellite aboard an Athena I rocket, the first planned mission to low earth orbit from the new facility. To support this launch, a statistical model of the atmospheric and surface environment for Kodiak Island, AK has been produced from rawinsonde and surface-based meteorological observations for use as an input to future launch vehicle design and/or operations. In this study, the creation of a "reference atmosphere" from rawinsonde observations is described along with comparisons between the reference atmosphere and existing model representations for Kodiak (Rawlins and Johnson, 2000). Meteorological conditions that might result in a delay on launch day (cloud cover, visibility, precipitation, etc.) are also explored and described through probabilities of launch by month and hour of day. This atmospheric "mission analysis" is also useful during the early stages of a vehicle program, when consideration of the climatic characteristics of a location can be factored into vehicle designs.

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To be most beneficial, terrestrial environment definitions should a) be available at the inception of the program and based on the desired operational performance of the launch vehicle, b) be issued under the signature of the program manager and be part of the controlled program definition and requirements documentation, and c) specify the terrestrial environment for all phases of activity including pre-launch, launch, ascent, on-orbit, decent, and landing (Pearson, et al., 1996). Since the beginning of the space era, NASA has utilized some of the most detailed assessments of the terrestrial climatic environment in design, development, and operations of both expendable and reusable launch vehicles. Projects such as the Saturn V, Space Transportation System (STS), also known as the Space Shuttle program, and new programs such as X-33 and X-37 have all relied on environments definitions from both observed meteorological data (Meteorology Group Range Commanders Council, 1983) and atmospheric models (Adelfang et al., 1994; Justus and Johnson, 1999).

2. U.S Standard Atmosphere

The first modern standard atmosphere was developed in the early 1920's by United States and European advisory committees in order to establish standardization of aircraft instruments and performance (COESA, 1962). A standard atmosphere, as defined by the World Meteorological Organization (WMO) is, ". . A hypothetical vertical distribution of atmospheric temperature, pressure, and density which, by international agreement, is roughly representative of year-round, mid latitude conditions. . ." (U.S. Standard Atmosphere, 1976). Developed from theory, these tables contained values of atmospheric properties to a geopotential altitude of 300 km. Sponsors of this effort included NASA, the National Oceanic and Atmospheric Administration (NOAA), and the United States Air Force. In time, reliable rocket and satellite data made possible the definition of atmospheric properties up to 1,000 km and in 1961 a new Working Group of the Committee on Extension to the Standard Atmosphere (COESA) was convened with the task of developing a new standard atmosphere. The *U. S. Standard Atmosphere, 1962* is divided into four altitude ranges, -5 to 20 km, 20 to 32 km, 32 to 90 km, and 90 to 700 km. A revision incorporating new solar data was published in 1976, and subsequent analysis showed that densities are about 10% lower in the 70- to 80-km region and 10% higher in the 90-km region than in the 1962 Standard (U. S. Atmosphere, 1976).

3. Global Reference Atmospheric Model

Standard atmospheric models have been used repeatedly over the years for aerospace vehicle design and mission planning. However, early models such as the U. S. Standard Atmosphere (1962 and 1976) have no spatial variability and only limited temporal variability. The NASA/MSFC Global Reference Atmospheric (GRAM) fills this void. GRAM contains gridded (2.5 X 2.5 degree) monthly mean estimates of wind and thermodynamic parameters derived from rawinsonde and aircraft observations (Justus and Johnson, 1999), and provides complete global geographic coverage and altitude coverage from the surface to orbital altitudes. GRAM also has the capability to simulate spatial and temporal perturbations representing phenomena such as turbulence, mesoscale processes, and baroclinic waves.

GRAM-99, the latest version of the model, is a combination of three empirically based models that represent different altitude ranges. The Global Upper Air Climatic Atlas (GUACA) covers altitudes from 0 to 27 km (Ruth et al., 1993). Altitudes from 20 to 120 km are represented by data from Middle Atmosphere Program (MAP) (Labitzke et al., 1985), and regions above 90 km are simulated by the Jacchia model (Jacchia, 1970). GRAM-99 employs a fairing procedure to ensure a smooth transition from one data set to the next in regions where the data sets overlap. The model also allows for use of the newer Global Gridded Upper Air Statistics (GGUAS) data in the lower altitude region in place of the GUACA data set. For details of GRAM-99, the GUACA data, and the GGUAS the reader is referred to Justus and Johnson (1999).

A new feature of GRAM-99 is the option to use data from a set of Range Reference Atmospheres (Meteorology Group Range Commanders Council, 1983) as an alternate to the GRAM data for a flight profile near a particular range. Beginning in 1963, a series of technical documents characterizing wind components and atmospheric thermodynamics were produced for a number of launch sites both in the United States and abroad. Derived from the best available upper atmosphere data from rawinsondes and rocketsondes, the Range Reference Atmospheres contain tabulations of monthly and annual means, standard deviations, and skewness coefficients for wind and atmospheric thermodynamics from the surface to 30 km, or surface to as high as 70 km when data from rocketsondes were available. Skewness is a measure of the lack of symmetry in a probability distribution. For example, a normal distribution has zero skewness, and a log normal distribution is positively "skewed". In order to maintain a level of standardization, the modeling code, publication text and table format for each Range Reference Atmosphere was to be identical. To maintain consistency, the Rawlins and Johnson (2000) document contains tabulations and statistics that mirror these documents.

4. Rawinsonde and Surface Data for Kodiak

Atmospheric thermodynamics and wind parameters (mean speed, direction, and U and V components) are computed from a set of twice-daily rawinsonde ascents for Kodiak, AK from 1973-1995. Temporal consistency of the data is very good, with an average of ~60 soundings per month through the period. Quality Control procedures, including vertical consistency and limits checks were applied to each sounding in order to eliminate erroneous data. Soundings were also screened for obvious errors such as wind directions greater than 360° or less than 0° or air temperatures greater than 40 °C (104 °F). Further checks ensured that pressures decreased through the sounding. Soundings passing quality control checks were interpolated to 50-meter intervals from the surface to 30 km and then averaged (by month) over the period 1973-1995 to create the "Empirical" Kodiak Reference Atmosphere (KRA). Only data at mandatory reporting levels was used to create each individual interpolated profile. Tabulations of wind speed, pressure, temperature, density, water vapor pressure, virtual temperature, and dewpoint temperature at 1 km intervals comprising the KRA, as well as details of the interpolations to the vertical grid, additional analysis, and documentation are presented in the Rawlins and Johnson (2000) report.

Climatological data for Kodiak used in the atmospheric "mission analysis" are taken from the standard (historical) hourly surface weather observations. Data utilized in this study are drawn from the period 1970-1996. From a total of 39 available weather parameters, cloud ceiling height, total sky cover, visibility, occurrence of thunderstorms, and occurrence of precipitation provide the 5 inputs used to illustrate the importance of an atmospheric mission analysis in aerospace programs.

5. Atmospheric environment of Kodiak, AK

Wind

Mean wind speeds tabulated in the KRA are examined to characterize the general vertical and seasonal distribution from the surface through 30 km. Speeds are greatest at approximately 10 km with mean values being over 25 m/s (Figure 1), although mean winds can readily exceed 70 m/s in more intense storms. Winds are generally light in summer, particularly between 20-25 km. Examination of the U and V components (Figure not shown) reveals winds to be generally west-southwesterly during much of the year, however both zonal and meridional winds are very light (< 10 m/s) in summer. Zonal winds are typically westerly, with easterly winds in summer between 22 and 30 km, and below 5 km.

Differences between wind components in the KRA and those represented in GRAM-99, illustrate the accuracy of the GRAM model. U component differences are small, only exceeding 4 m/s between 12 and 22 km in December (Figure 2), with most deviations less than 2 m/s. Differences in the V components

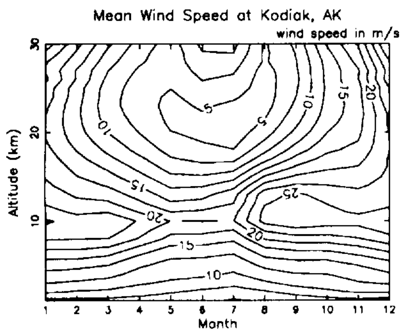

Figure 1. Mean wind speed at Kodiak, AK.

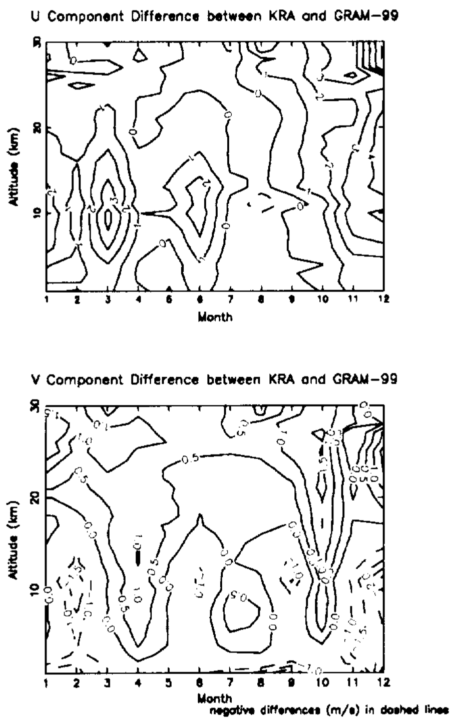

Figure 2. Wind component differences between the KRA and GRAM-99. Differences (m/s) are defined as KRA value minus GRAM-99.

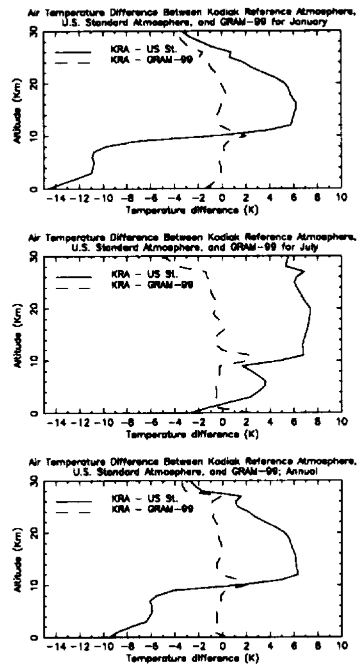

Figure 3. Air temperature differences between the KRA, U. S. Standard Atmosphere, and GRAM-99 for January, July, and Annual mean temperatures.

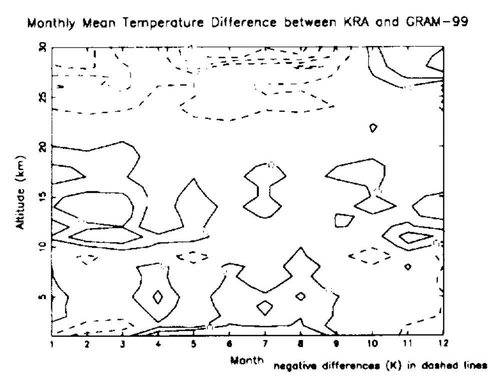

Figure 4. Differences in mean monthly temperature between the KRA and GRAM-99.

(which are considerably lower than the U components) are generally less than 1.5 m/s.

Air Temperature

For over 40 years, the U. S. Standard Atmosphere has been the benchmark definition of the mid latitude atmosphere for the aerospace industry. With the development of the Global Reference Atmospheric Model (Justus and Johnson, 1999) engineers have been able to assess seasonal and geographic variability for locations where the U. S. Standard Atmosphere may not be sufficiently accurate. Indeed differences in air temperature between the new KRA and the U. S. Standard Atmosphere are substantial, particularly when comparing January temperatures below 10 km where, as one might expect, the KRA temperatures are 6-15 K colder (Figure 3). January temperatures in the 10-20 km region are relatively warmer than the U. S. Standard Atmosphere, owing in part to the shallow depth of the troposphere at higher latitudes. This fact is evident in July temperatures as well, with KRA values 6 K warmer than the Standard Atmosphere above 10 km. A similar pattern is also evident in annual temperatures.

GRAM-99 estimates of air temperature at Kodiak are in much better agreement with the KRA values (Figures 3 and 4) than the KRA/U. S. Standard Atmosphere comparisons. Differences are less than +/- 2 K from the surface to 26 km in both January and July, with the KRA estimates being slightly colder. Annual temperatures are in very close agreement; differences are small through most of the profile. Across all months, deviations are generally less than +/- 1 K, with the exception of altitudes above 27 km, where the KRA estimate are 2-4 K colder than the GRAM-99 representations (Figure 4).

Density

Atmospheric density is one of the more important inputs in terrestrial environment definitions for aerospace applications. Density affects flight performance, aerodynamic heating, and vehicle load stresses to name a few. Variability in density can be illustrated through the coefficient of variation, defined as the standard deviation divided by the mean. For 1-km densities derived and tabulated in the new KRA, minimum variability in January density occurs at 2-3 km, which is referred to as the isopycnic level, while a maximum is found at 11 km (Figure 5). In July a broad minimum occurs from the surface to 10 km and like January, the maximum is near 11 km. As one might expect, the coefficient of variation is larger for annual density, since the means and standard deviations are determined from all derived densities at a given altitude over the year.

Density differences between the KRA and U. S. Standard Atmosphere, as was the case with air temperature differences, are relatively large (Figure 6). For density we define the differences in percent, relative to the KRA densities. In January KRA density is less than the U. S. Standard Atmosphere value through most of the profile (due to a warmer layer in the U. S. Standard Atmosphere), exceeding 6% difference from 10-20 km. Deviations are smaller in July, with percent differences greater than 4% between 20-27 km only. Annual density differences, like those in January, are non-trivial; KRA density is less than the U. S. Standard Atmosphere by greater than 5% from 10-16 km, and again between 27-30 km.

Comparisons between the KRA and GRAM-99 reveal very close agreement in most cases. Differences are within 1% through most of the January, July and annual profiles (Figure 6), with differences exceeding 1% above 26 km in January and above 28 km for annual density. Over all months, percent differences are again small, exceeding 1% at a few altitudes/months (Figure 7). It is apparent that the GRAM-99 depiction of atmospheric density at Kodiak is in very good agreement with the historical twice-daily rawinsonde observations used to create the KRA.

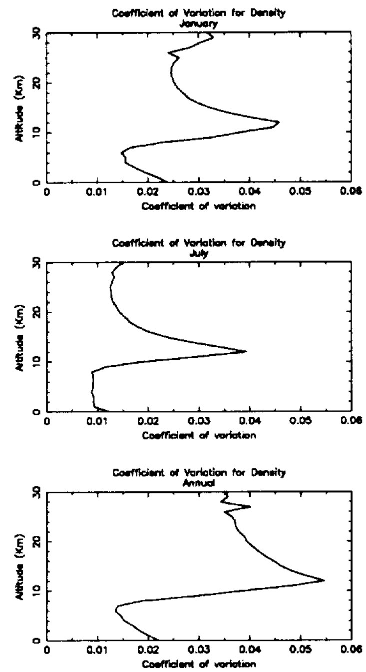

Figure 5. Coefficient of variation for January, July, and Annual mean density.

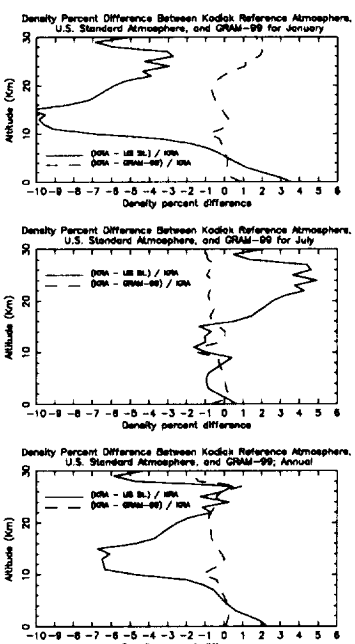

Figure 6. Density differences between KRA, U. S. Standard Atmosphere, and GRAM-99 for January, July, and Annual mean density.

6. Surface Climatological Analysis

Terrestrial environment factors, or more specifically weather-related variables, can have a great impact on the probability of achieving a successful launch. Characterization of the surface environment is also vital in the design phase of a new launch vehicle. Most statistical summaries of weather- related variables are made for single parameters or a combination of a few variables. However, interest is not only in the

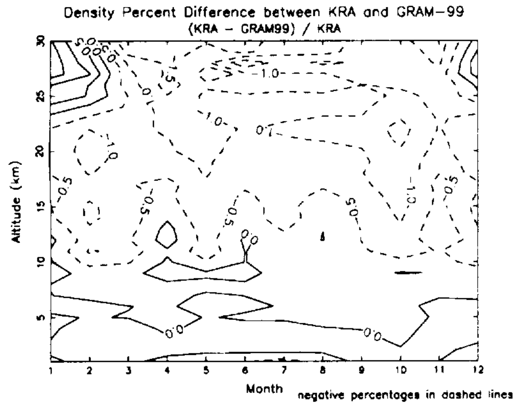

Figure 7. Percent density difference between KRA and GRAM-99. Difference is KRA minus GRAM-99 divided by KRA value * 100.

probability of occurrence for each of the individual events taken separately but also in the chance that at least one of those events will occur during any particular phase of the mission (Johnson, et al., 1997). For example, there may be constraints due to several environmental parameters, with the occurrence of any one of the conditions constituting a "No-Go" situation. An atmospheric "mission analysis" is often used to answer questions such as a) what is the probability that a particular event will (will not) occur during a given reference period, b) what is the probability that a particular event will (will not) occur for N consecutive days during a given reference period, and c) once a designated condition has (has not) occurred for N consecutive days at a particular time of day, what is the probability that the given condition will continue for N additional days (Johnson, et al., 1997).

An atmospheric mission analysis for Kodiak was performed using hourly surface weather data for the period 1970-1996. To illustrate the effect on Go-NoGo probabilities, the mission analysis was run for two relatively disparate sets of constraints. In both cases no thunderstorms or precipitation was allowed. For case 1, visibility cannot be < 10 nautical miles, cloud ceiling < 10,000 feet, or total sky cover > 0.5. In case 2, a very liberal set of constraints was set. Visibility was relaxed, and cannot be to < 1 nautical mile, cloud ceiling < 2,000 feet or total sky cover > 0.9. Tables 1 and 2 list the probabilities that at least one of the constraints will occur, listed by hour and month, based on empirical data for the period 1970-1996. For case 1, No-Go conditions were present 75.4% of the time (on average), with late morning hours during summer being the most challenging launch environment. No-Go probabilities are significantly decreased for the more relaxed set of meteorological conditions (Case 2); sufficient conditions are met an average of 54.2% of the time. Early morning hours in autumn provide the best opportunity for launch, with average probabilities of just over 40% (Table 2). Examination of the individual meteorological parameter probabilities (Tables not shown) indicates that visibility

Table 1.

NOGO Probabilities in percent

hr LST	J	F	M	A	M	J	J	A	S	O	N	D
0	78	78	72	78	79	81	77	75	76	69	69	74
1	77	76	73	77	78	80	78	76	76	69	71	74
2	84	85	81	84	83	82	82	80	81	77	81	81
3	78	75	73	76	78	81	79	76	75	68	73	77
4	79	76	73	79	77	81	78	74	74	65	73	76
5	84	83	80	78	79	79	81	74	76	74	80	83
6	77	74	72	80	78	84	81	76	71	66	72	76
7	75	72	68	77	78	83	80	76	74	63	69	74
8	76	71	69	77	80	81	80	74	75	66	68	72
9	72	69	68	77	79	86	81	73	74	63	66	71
10	73	72	68	78	80	86	81	73	73	64	66	72
11	75	71	67	77	81	81	81	74	73	66	67	71
12	76	69	66	76	81	85	81	75	74	65	66	73
13	76	72	67	77	80	84	81	76	75	68	66	74
14	75	71	69	76	82	79	79	76	75	70	68	73
15	76	69	68	76	78	82	79	77	75	68	68	76
16	77	70	68	76	78	82	79	77	75	68	67	75
17	77	71	68	75	79	77	77	76	76	71	70	79
18	74	71	69	75	77	79	79	75	77	67	67	77
19	75	73	68	74	77	80	80	74	75	68	69	77
20	81	80	77	76	78	75	79	73	78	77	77	84
21	76	74	69	76	76	79	79	72	73	72	70	77
22	78	75	69	75	76	78	79	73	73	71	70	77
23	84	83	79	82	81	78	81	79	78	76	77	82

Overall percent average = 75.4

Table 2.

NOGO Probabilities in percent

hr LST	J	F	M	A	M	J	J	A	S	O	N	D
0	57	54	52	59	59	63	60	49	49	41	45	54
1	55	56	51	58	60	65	61	50	51	41	46	54
2	58	57	51	58	62	61	60	52	51	44	48	52
3	56	54	51	58	60	66	61	50	50	41	46	54
4	57	56	51	60	61	68	61	51	49	40	49	54
5	60	56	51	56	62	64	63	53	49	43	45	52
6	59	54	50	61	62	68	61	53	49	41	47	54
7	56	53	50	60	62	69	62	53	51	40	46	53
8	56	57	52	60	65	65	64	54	53	45	48	52
9	54	56	53	60	62	71	61	48	50	42	48	53
10	54	59	51	61	60	68	61	49	50	43	48	55
11	57	58	51	58	62	63	59	51	50	45	48	56
12	56	55	51	58	61	67	58	45	48	43	47	56
13	57	54	51	55	59	65	56	46	47	43	47	56
14	58	54	51	55	60	59	56	48	47	47	50	56
15	56	54	52	57	56	62	55	46	46	45	52	60
16	57	55	52	55	55	60	56	47	46	46	50	61
17	58	57	50	55	58	57	56	49	49	49	49	59
18	57	55	52	57	56	61	56	48	47	49	48	61
19	58	56	52	57	57	61	59	47	46	47	48	59
20	59	55	52	58	60	56	58	50	49	47	48	56
21	56	54	54	60	59	61	59	49	49	45	48	57
22	57	54	53	60	61	63	61	49	49	46	46	58
23	59	53	53	57	62	60	60	52	48	44	46	52

Overall percent average = 54.2

is the most sensitive parameter. Requiring a minimum visibility of 10 nautical miles causes a No-Go probability of approximately 35% (averaged over all hours/months). By relaxing visibility to a minimum of 1 nautical mile, No-Go probabilities from the visibility constraint are reduced to an average of 1%. Cloud ceiling is the next most sensitive constraint; average No-Go probabilities are nearly halved when requiring a 2,000 feet ceiling versus the more stringent 10,000 feet requirement. Total sky cover has the smallest impact on probabilities. It should be noted that the constraints in case 1 should not be considered unreasonable for most launch vehicles. But regardless of the precise environmental constraints imposed, Kodiak Island, Alaska is clearly a challenging environment for mission success, particularly during morning hours in summer months.

7. Summary Remarks

Launch vehicle design and operation are dependent on accurate definitions of the terrestrial environment for mission success. A new reference atmosphere for Kodiak, Alaska has been developed from historical rawinsonde observations and compared to the U. S. Standard Atmosphere and GRAM-99. Substantial disparity is noted between the Kodiak Reference Atmosphere (KRA) and the U. S. Standard Atmosphere, which was developed to represent a typical mid latitude environment. Excellent agreement is evident between the KRA and GRAM-99 for wind components, air temperature and density, particularly below 25 km where the GRAM model primarily utilizes the GUACA database.

Analysis of Go-NoGo probabilities due to launch weather constraints reveals relatively high No-Go probabilities when using typical meteorological requirements. Probabilities of encountering adverse weather conditions by hour and month can be greater than 75% for the typical requirements, suggesting that careful launch scheduling may be prudent to avoid costly delays. Hourly weather data used in the atmospheric mission analysis was gathered at Kodiak City, AK, which is approximately 40 miles north of the Kodiak Launch Complex at Narrow Cape. It is possible that adverse weather conditions (low clouds, fog) at the launch site may be worse than the statistics indicate, depending on the prevailing wind direction.

Rocketsonde data previously has been used to estimate winds and atmospheric thermodynamics above typical rawinsonde ascents. However, none exists for Kodiak. Incorporation of satellite estimates, nearby rocketsonde data or other representative information may prove useful in the future. A comprehensive report detailing the Kodiak Reference Atrmosphere, the surface environment, and additional descriptions and analysis is being planned for use in future launch vehicle designs and/or operations.

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